Hyperspectral Modeling of Harmful Algal Blooms on the West Florida Shelf

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LONG-TERM GOAL

Construction and validation of a coupled physical/ecological/bio-optical simulation of phytoplankton, colored dissolved organic matter, and suspended sediments on the West Florida Shelf. This simulation will be used to test the hypothesis that the spectral quality and quantity of the available photon flux are two of the determining factors in the initiation of *G. breve* blooms on the West Florida Shelf.

OBJECTIVES

The occurrence of Harmful Algal Blooms [HABs] on the West Florida Shelf [WFS] in 21 of the last 22 years has caused massive fish, invertebrate, and bird kills. In an attempt to discern the casual mechanisms for these HABs, NOAA/EPA/ONR established the Ecology and Oceanography of Harmful Algal Blooms [ECOHAB] program on the WFS. ONR's participation in ECOHAB on the WFS is part of a larger effort to simulate the inherent and apparent optical properties [IOPs and AOPs] using the West Florida shelf as an initial test case. The ONR HyCODE [Hyperspectral Coastal Ocean Dynamics Experiment] and ONR AUV [Autonomous Underwater Vehicle]-Sensor programs are augmenting the ECOHAB field and modeling programs in order to provide a complete physical, biological, chemical, and optical time series over the ~11,000 km ECOHAB study area. My objective is to couple a hyperspectral optical model that incorporates constituent specific optical properties to an ecological model of seven functional groups of competing microalgae. The resultant simulation is to be physically forced at different spatial scales and validated by moored, aircraft, and satellite optical data streams. This simulation will be used to test whether the spectral light harvesting abilities of *G. breve* (which includes pigment optimization and diurnal migration) provides a negative feedback on the total phytoplankton community, enhancing the competitive capabilities of *G. breve* for other necessary resources (i.e., nutrients).

The ECOHAB studies focus on a control volume, which extends between the 10-m and 50-m isobaths along the Florida coast from Tampa Bay to Charlotte Harbor. This volume is sampled at monthly intervals with continuous underway measurements of u, v, temperature, salinity, *in vivo* chlorophyll fluorescence, CDOM, and transmissometry as part of the ECOHAB hydrographic cruises. At discrete stations, additional data are now collected on distributions of NO_3, NO_2, NH_4, PO_4, SiO_4, Fe (III), DOP, DON, DIC, DOC, CDOC, chlorophyll, phaeopigments, PN, PC, PP, $\delta^{15}N$ of PN and NO_3, cell counts of all dominant phytoplankton species, and abundance of micro- and macrozooplankton species. The control volume is now bounded by an ADCP array that will provide continuous sampling of depth-dependent horizontal velocity components at the volume corners, and selected interior locations. As part of the ONR participation in the project, additional interior ADCP arrays of the control volume

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will support a suite of moored optical sensors: hyperspectral radiometers, backscatterometers (660 and 880 nm), c-meters (288 and 660 nm), and fluorometers (chlorophyll and CDOM). On supplemental cruises at 2-month intervals, other discrete measurements of turbidity, and spectral dependence of absorption, backscatter, water-leaving radiance, and light attenuation will be made.

Additional cruises are planned during the summer and fall of 2000. These experiments will focus on SF_6 dispersion studies, and are planned in relation to aircraft over-flights and underway sampling of plankton particles [OPC, LS] and images [SIPPER]. These over-flights will carry the NRL hyperspectral imaging spectrometer [Ocean PHILLS]. As high-resolution hyperspectral data is anticipated to be the best source of initialization and validation data for the 3-D ecological simulations, these flights are critical to our development of the models. In anticipation of numerical synthesis of these diverse data sets, we have begun retrospective simulation studies of the biological and chemical sources of IOPs and $L_w(\lambda)$ over the last 40 years on the West Florida shelf.

APPROACH

Ecological modeling of phytoplankton is still in a state of infancy. Most attempts at simulating the microalgal content of the water column rely on reproducing the areal distribution of chlorophyll a. However, chlorophyll a does not adequately describe the total assemblage, or the individual components, of the phytoplankton community. Thus, the assumption of adequacy in reproducing fields of chlorophyll a with simplified numerical schemes fails to address the ecological interactions that are critical to HABs. Our approach is to simulate the dominant functional groups of the phytoplankton assemblage with their attendant sources and sinks. In this way, we hope to develop prognostic simulations of the optical, chemical, and biological responses to the physical forcing on the WFS.

The problem with a simplified modeling approach is demonstrated by the fact that a “red” tide of *G. breve* is approximately 1×10^6 cells/ml. This is approximately 10 μg chl a liter^{-1}, and would thus represent the dominant functional group of phytoplankton on this normally oligotrophic shelf. The problem occurs because this phytoplankton species has a maximum growth rate of ~0.2 d^{-1}. Nutrient stocks sufficient to support such a large accumulation of phytoplankton biomass would typically be exhausted by a faster growing phytoplankton species (diatoms have maximum growth rates of ~3.0 d^{-1}, microflagellates and coccoid cyanobacteria - ~2.0 d^{-1}, dinoflagellates - ~1.5 d^{-1}). In order for *G. breve* to win in a competition for resources, they must have competitive advantages that select for their survival and accumulation to toxic concentrations. It is this competitive selection that must be simulated to prognostically relate physical forcing to ecological succession. By extension, accurate simulation of ecological succession means we accurately simulated the inherent and apparent optical properties of the water column.

This work is part of a larger ONR modeling effort on the WFS to build a predictive optical simulation. The PIs of this modeling effort include J.J. Walsh and R.H. Weisberg at USF [University of South Florida], and R.W. Garwood at NPS [Naval Postgraduate School]. A brief description of these projects can be found at the end of this report. In addition, we are working with D. Stramski [Scripps Institute of Oceanography], O. Schofield [Rutgers University] and M. Moline [California Polytechnic State University] to develop particle-specific optical properties for the phytoplankton functional groups over a wide-range of nutrient, light, and temperature conditions. In particular, this effort will focus on the time-, nutrient-, light-, and temperature-dependent optical response equations for each group. The hyperspectral data collection and analysis is being accomplished in collaboration with Curtiss O. Davis, Jeffry Bowles, and Mary Kappus [Naval Research Laboratory], Kendall Carder [University of

South Florida], and Robert Maffione [HOBI Labs]. Lastly, we are working with Curt Mobley [Sequoia Scientific, Inc.], Marcos Montes [Naval Research Laboratory] in developing a reduced resolution version of Hydrolight 4.0 to be used in conjunction with a 3-dimensional EcoSim to predict $R_{rs}(\lambda)$ and $L_w(\lambda)$ at 10:00 am each day. These predicted AOPs are to be directly compared against remotely sensed data from moorings, aircraft, and satellite sensors.

WORK COMPLETED

This past year has been focused in three areas.
1) The establishment of the functional groups to be modeled; their ecological interactions and parameters; developing the methodology to simulating time-dependent changes in particle-specific absorption, scattering, and scattering phase function.
2) The collection of hyperspectral data and its analysis.
3) Lastly, the development of a method to produce $L_w(\lambda)$ and $R_{rs}(\lambda)$ from EcoSim.

RESULTS

The ecological parameters for the 7 groups of phytoplankton can be briefly seen in Table 1. These parameters are for the initial development of EcoSim–WFS, and represent the "Redfield" case, where the intracellular pools of organic constituents do not change as a function of light and nutrient conditions. These will be combined with the static cellular IOP description for each functional group. There are two reasons for static descriptions of the organic pools and particle specific-optical properties. First, it is a more numerically efficient coding scheme, and error propagation is more easily discerned in a large 3-D scheme. Second, the data for variations in intracellular stocks of C, N, P, Fe, and Si, as well as the complete IOP description as a function of growth rates and nutrient conditions do not presently exist. We are currently working with a number of research groups to obtain this data, and will incorporate it as it becomes available.

A sample of the results from the ECOHAB/NRL Spectral Signatures over-flights in October 1998 can be found in Figure 1. The over-flights occurred over a two week period and coincided with a multi-ship field operation that collected ecological, hydrographical, and optical validation data. Figure 1 is a pseudo-RGB image of data taken at 10,000 feet over the Sunshine Skyway Bridge and was used as part of a vicarious calibration exercise. There are instrument calibration and data quality issues that are still being resolved, and it is unclear whether this data can be made useful. The Ocean PHILLS has undergone a refit since this experiment (see ONR COBOP program), and we may have to wait until the 2000 over-flights to obtain usable data.

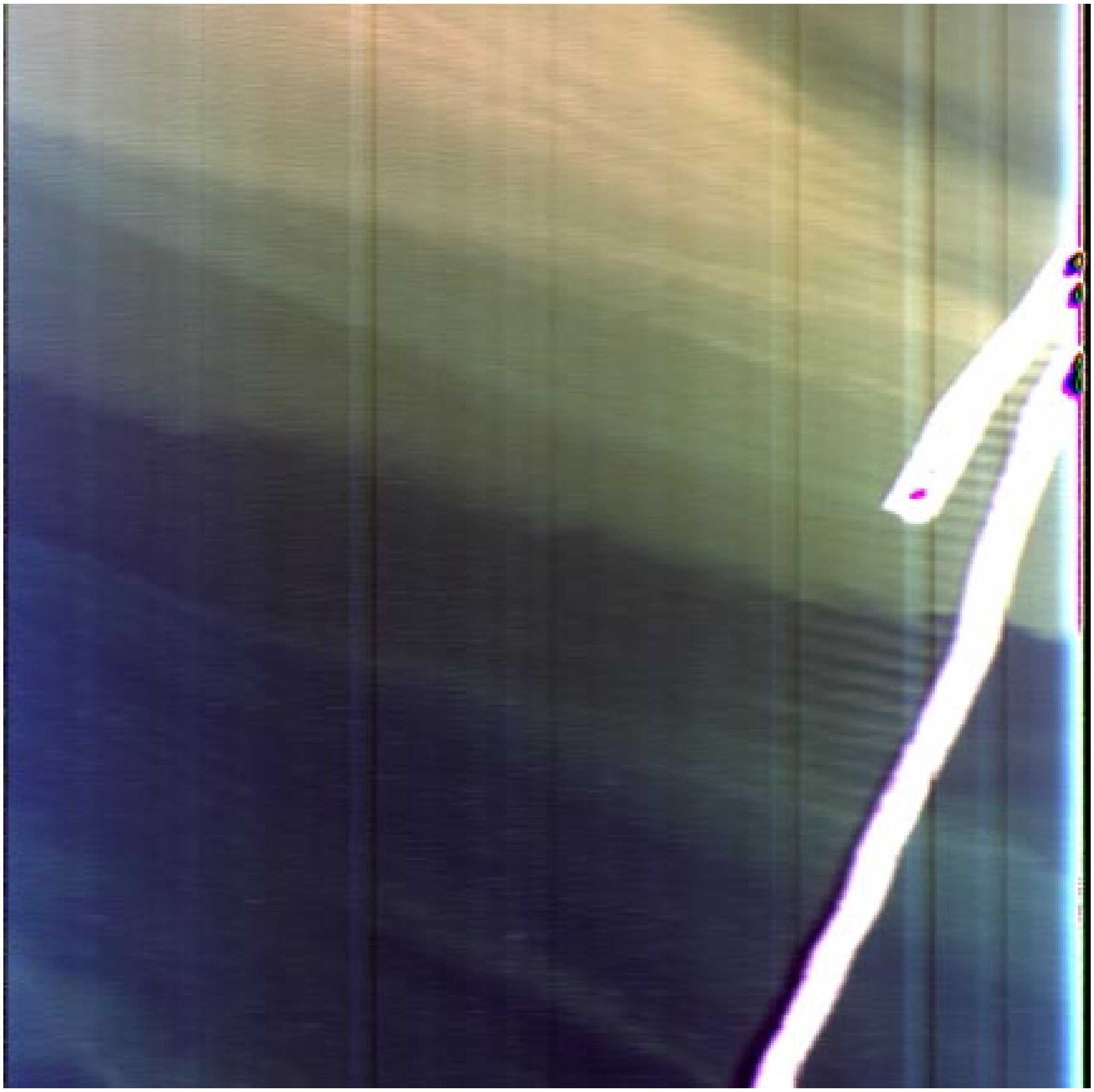
Figure 2 shows a comparison of EcoSim 1.0 predicted chlorophyll a in the Sargasso Sea versus a compilation of the 6 years of CZCS data at the site folded into a single year time-series CZCS. The first 2 lines were published in 1999 [Bissett et al., 1999, Deep-Sea Research, V42:271-317]. The third line is the output from a SeaWiFS algorithm [Carder et al., 1998, Journal of Geophysical Research, MODIS Special Issue] that uses $R_{rs}(\lambda)$ at 412, 443, 490, 510, 555, 670 to estimate the chlorophyll a concentration. EcoSim $R_{rs}(\lambda)$ was calculated with a modified version of Hydrolight 3.0 that ingested the predicted IOPs from the daily output of EcoSim 1.0 to yield daily above-water reflectance values (as well as, depth-dependent AOPs). The major discrepancy is in the summer when the SeaWiFS chlorophyll a is much higher than EcoSim and CZCS. This result is expected since the IOPs in EcoSim 1.0 utilized 'Smith and Baker, 1981' absorption values for "pure" seawater. These pure water absorption values have been shown to be too high in the blue [Pope, 1993, Ph.D. Dissertation, Texas

A&M University, College Station]. The SeaWiFS uses more accurate values for pure water absorption. The differences between the ‘Smith and Baker’ and the Pope absorption values is most noticeable during the summer when CDOM absorption is nearly non-existent in these waters. The SeaWiFS algorithm-estimated chlorophyll a is probably impacted by the erroneously high absorption values from EcoSim in the blue. The pure water absorption issue will be rectified in EcoSim 2.0.

Table 1. Competition parameters of functional groups of phytoplankton in relation to grazing stress effected by their predators, macrozooplankton (MZ) and protozoans (PN), during an annual cycle of thermal-modulated (15^oC to 30^oC) growth on the West Florida Shelf.

	Small diatom	Large diatom	*G. breve*	Other dino-flagellate	Cocco-litho-phore	Flag-ellate	*Tricho-desmium*	*Synech-ococcus*
Diameter (μm)	8	50	25	25	6	2	10	0.8
w_s (m day^{-1})	$[biomass]^2$		Disperse and/or migrate		1.5	0.0	buoyant	0.0
μ_{max} (day^{-1} @ 10^oC)	0.6	0.5	0.1	0.3	0.9	0.5	0.2	0.5
μ_{max} (day^{-1} @ 20^oC)	1.2	1.0	0.2	0.6	1.9	0.9	0.4	1.0
M_{max} (day^{-1} @ 30^oC)	2.4	2.0	0.4	1.2	0.6	1.8	0.8	2.0
I_{sat} (μE m^{-2} sec^{-1})	190	190	65	150	425	275	300	125
$K_{nitrate}$ (mmol m^{-3})	0.4	1.5	0.5	1.0	0.2	0.2	NA	0.2
$K_{ammonium}$ (mmol m^{-3})	0.8	1.0	0.5	0.9	0.1	0.2	NA	0.1
K_{DON} (mmol m^{-3})	NA	NA	0.1	0.2	NA	NA	NA	NA
$K_{phosphate}$ (mmol m^{-3})	0.4	0.4	0.2	0.2	0.4	0.6	2.0	2.0
K_{DOP} (μmol m^{-3})	NA	NA	10	10	NA	NA	10	NA
K_{iron} (μmol m^{-3})	0.1	0.3	0.2	0.2	0.05	0.04	1.0	0.03
$K_{silicate}$ (mmol m^{-3})	0.8	1.5	NA	NA	NA	NA	NA	NA
r_I (% μ_{max})	10	10	25	25	10	15	50	10
P_i (% MZ or PN)	60MZ	10MZ	1MZ	19MZ	60PN	90PN	10MZ	100PN
K_p (10^{-2} mg^{-1} Chl m^2)	4.8	2.3	3.5	4.8	4.8	5.7	4.8	6.5
C $cell^{-1}$ (pg)	32	1750	300	450	18	6	200	0.06
C/chl (pg pg^{-1})	55	45	30	45	75	100	200	30

Figure 1. Ocean PHILLS Pseudo-RGB – Sunshine Skyway Bridge



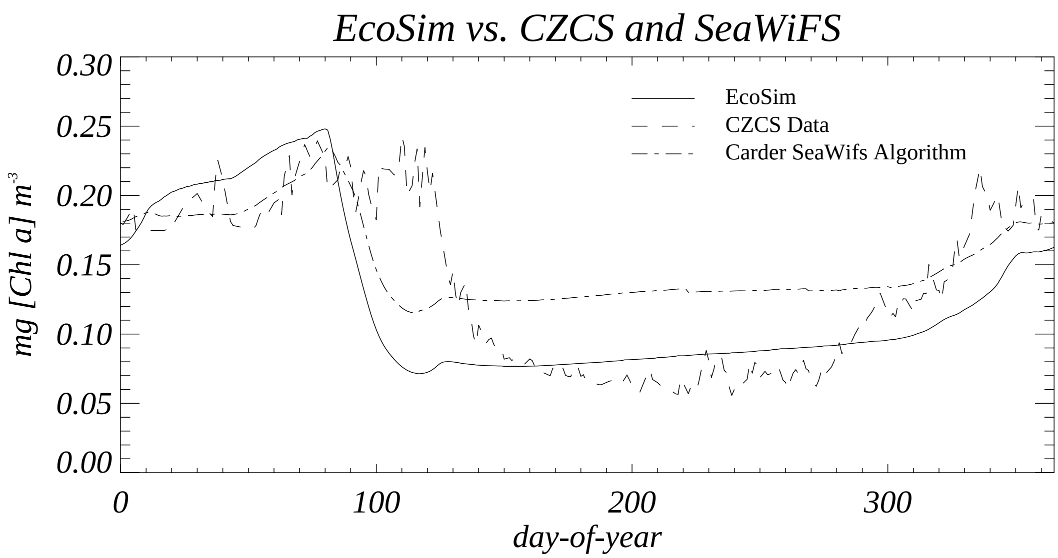
IMPACT/APPLICATIONS

Reasonable formulation of the physical, chemical, biological, and optical interactions of the marine environmental into a numerical simulation should provide us with the best opportunity to forecast the probability of a red tide occurrence on the West Florida Shelf. In addition, a validated simulation would also provide estimates of the depth-distribution of IOPs and AOPs. We expect to derive a transportable version of EcoSim to apply to Naval regions of interest.

RELATED PROJECTS

With support from N000149910212, John Walsh of USF is collaborating on the nutrient, physical, and ecological dynamics of our modeling effort.

Figure 2. Comparisons of EcoSim with CZCS data and Rrs-derived chlorophyll. The EcoSim line is predicted surface water chlorophyll a concentration using a seasonally-forced 1-D physical model in the Sargasso Sea. The CZCS line represents a six year time-series of pigment estimates folded into a single year time-series. The Carder SeaWiFS algorithm line represents calculated chlorophyll a from $R_{rs}(\lambda)$. This wavelength dependent reflectance was calculated from EcoSim predicted IOPs and Hydrolight 3.0 for every day of the year (365 independent runs to 150 m).



With support from N000149810158, Bob Weisberg of USF is responsible for the application of a primitive equation model at 5-km resolution to an analysis of the observed current fields on the West Florida shelf.

With support from N000149615024, Roland Garwood of NPS is using a non-hydrostatic Large Eddy Simulation [LES] model to compute small scale flows within the POM grid cells, since it is at the turbulence integral scale that physical processes accomplish most of the vertical mixing and dispersion of nutrients and plankton

With support from N000149910197, N000149910196, and N000149810003, Mark Moline [Cal Poly], Oscar Schofield [Rutgers] and Dariusz Stramski [Scripps] are helping to develop the particle-specific IOP equations.

Ken Carder of USF [N000149710006 and N000149910580] and Robert Maffione of HOBI Labs [N0001498C0345] are collecting in situ hyperspectral data to validate the over-flights and simulations.

With support from N0001497C0018 and N0001499C0019, Curt Mobley [Sequoia] is helping to develop an optimal radiative transfer code to be used in conjunction with a 3-D ecological simulation.

PUBLICATIONS

Schofield, O., J. Grzymski, W. P. Bissett, G. Kirkpatrick, D. F. Millie, M. Moline and C. S. Roesler (1999). “Optical monitoring and forecasting systems for harmful algal blooms: possibility or pipe dream?” Journal of Phycology: (in press).